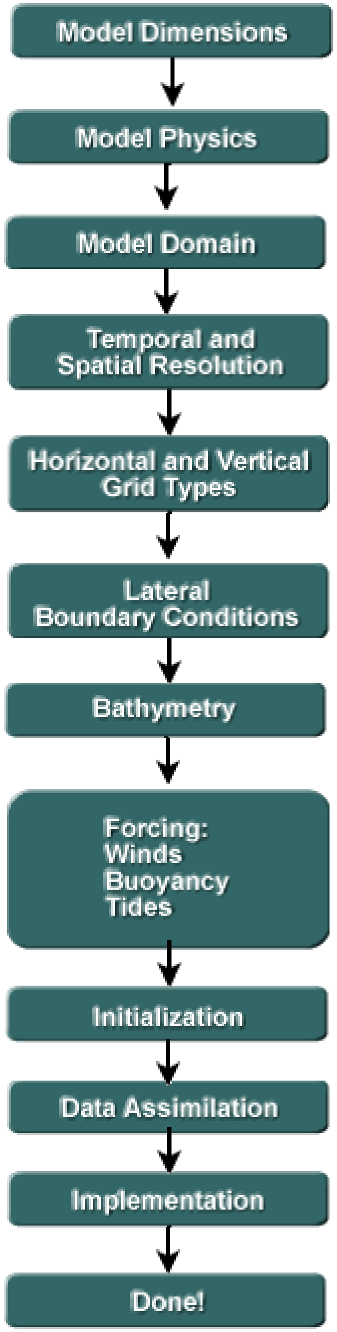


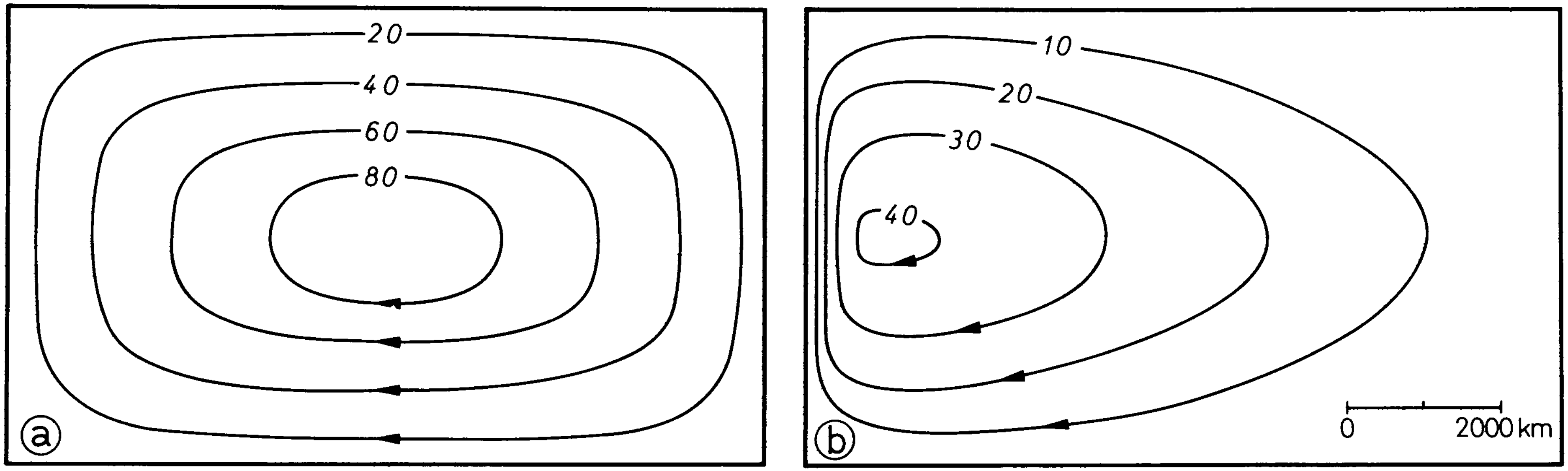

# Suggested reading

- If you want to learn more about how to design a numerical ocean model, an excellent source is

➔Numerical Ocean Modeling,

http://www.oc.nps.navy.mil/nom/modeling/index.html

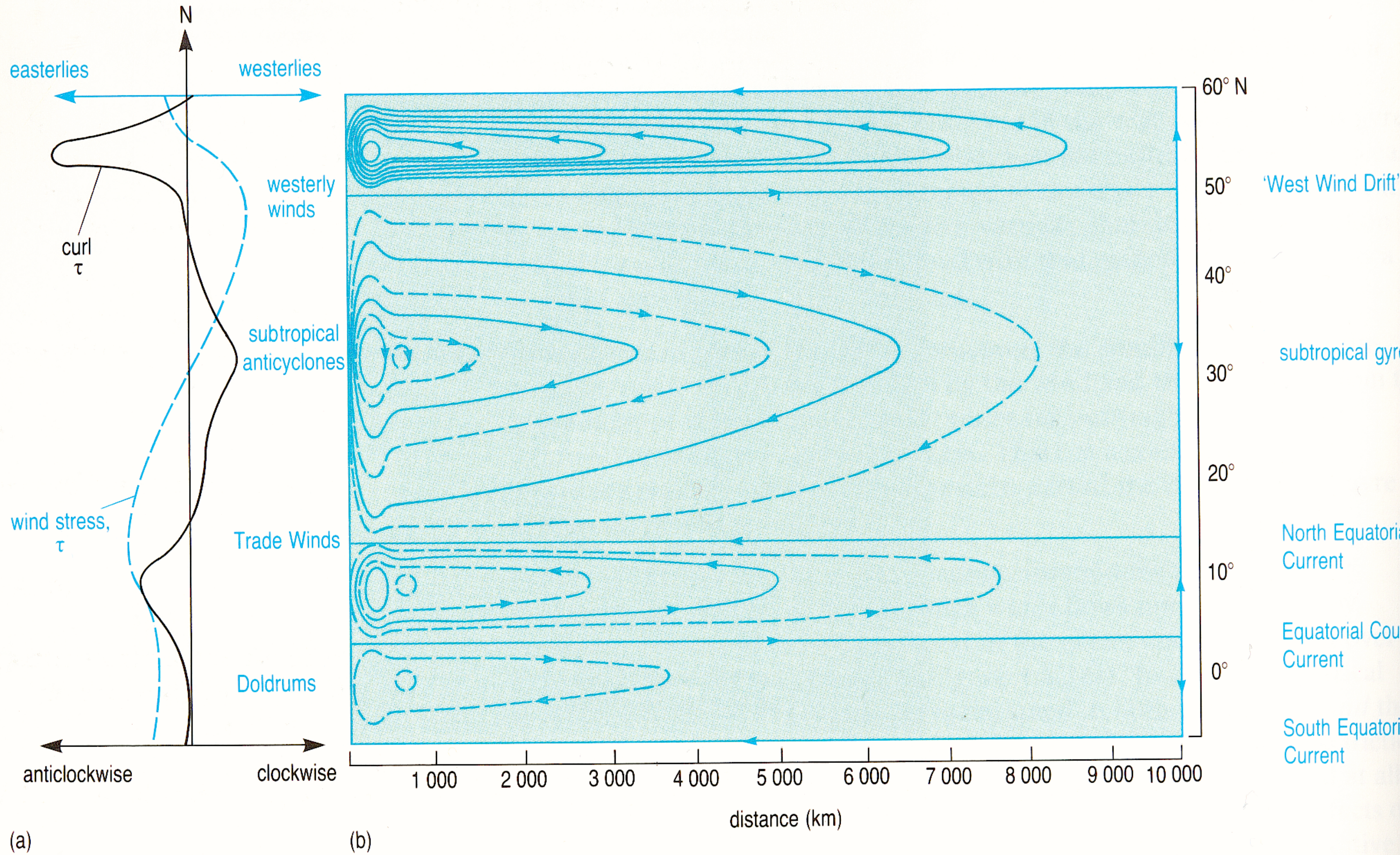
The ocean circulation model derived by Stommel (1948) already bears a strong resemblance to the circulatory systems of the subtropical gyre.




Stream lines (in units of Sverdrup, 1 Sv = $10^6$ m $s^{-1}$) in a rectangular basin with (a) constant Coriolis parameter and (b) latitude-dependent Coriolis parameter [Figure 7.20 from Dietrich et al. (1975)]

Improvements on ocean circulation model by Stommel:

- Munk (1950)
  - considered friction associated with lateral current shear
  - used the torque (curl) of the east-west component of the averaged winds of the real Pacific and Atlantic Oceans
- Hidaka (1951) treated the entire Pacific Ocean from 60°S to 60°N.




(a) Wind stress and its curl, (b) corresponding circulation pattern that Munk (1950) calculated [Figure 4.14 from Open University (1989)]

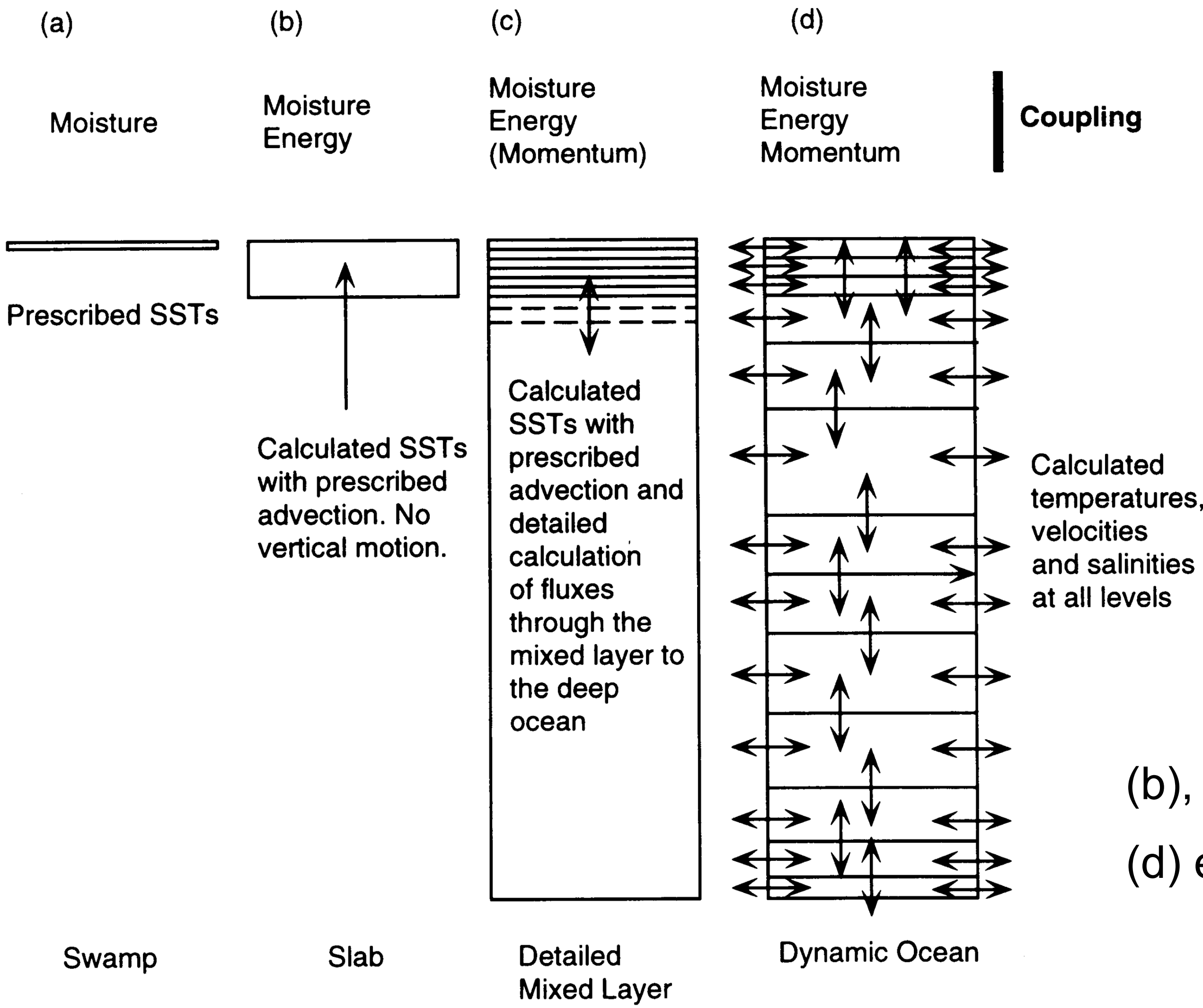
- Most modern models also include information about the transport of heat and salt, which are conservative properties.
  - Away from the sea-surface, they can only be changed by mixing.

Oxygen, dissolved inorganic carbon, nutrient concentrations and radiocarbon ($^{14}C$) are examples of non-conservative properties.

Based on Section 4.2.2 of Open University, 2nd edition

# History of ocean modeling

- The best known type of a three-dimensional ocean model was developed by Kirk Bryan at the Geophysical Fluid Dynamics Laboratory (GFDL, www.gfdl.gov) in Princeton in the United States in the late 1960s (cf. McGuffie and Hnederson-Sellers (2005), Section 2.3).
  - Modern descendents of this model are the “Modular Ocean Model” (MOM), the “Parallel Ocean Program” (POP) and the “Hadley Centre Ocean Model” (HadOM).




(b), (c) late 1980s

(d) early 1990s

Level of complexity and coupling to atmospheric models associated with various types of ocean models [Figure 5.10 from McGuffie and Henderson-Sellers (1997)]

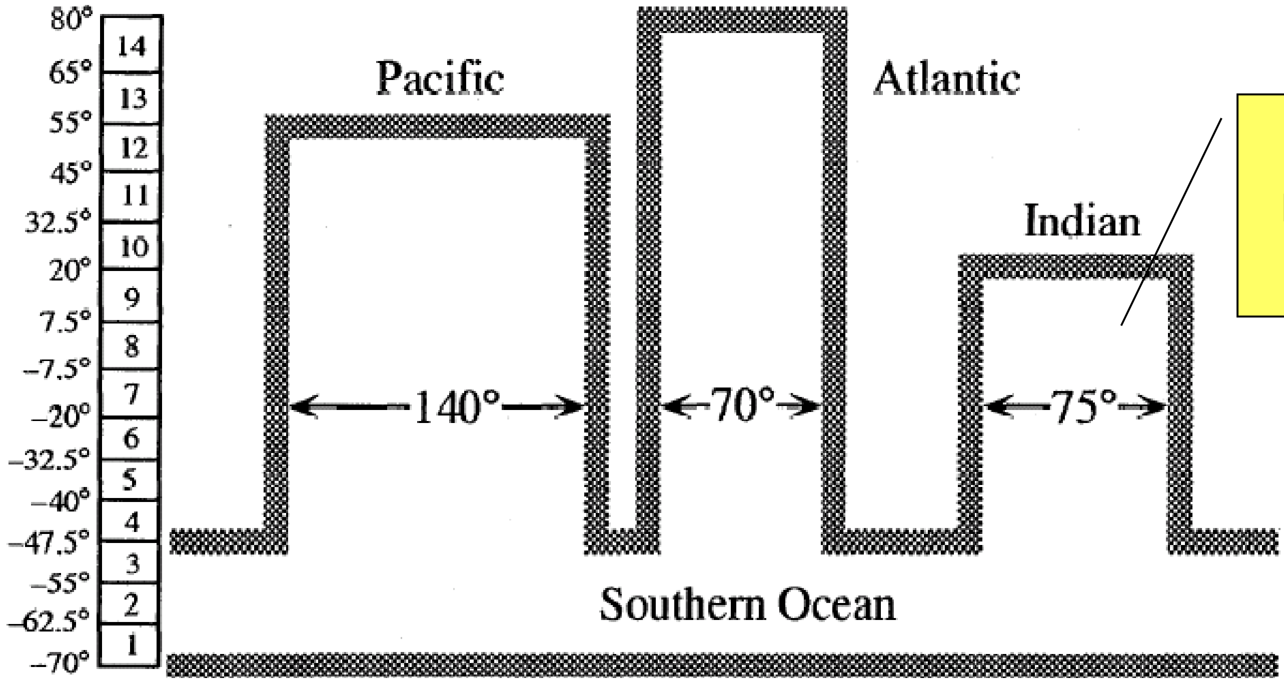
# Primitive equations

- Equations of motion
- Principle of continuity
- Conservation of heat and salt
- Equation of state (to relate temperature and salinity to density)

# Zonally-averaged ocean circulation models

- Based on zonally-averaged primitive equations
- Solved in zonally-averaged ocean basins (only latitude and depth are resolved)

# Wright-Stocker type zonally-averaged ocean circulation models: geometry



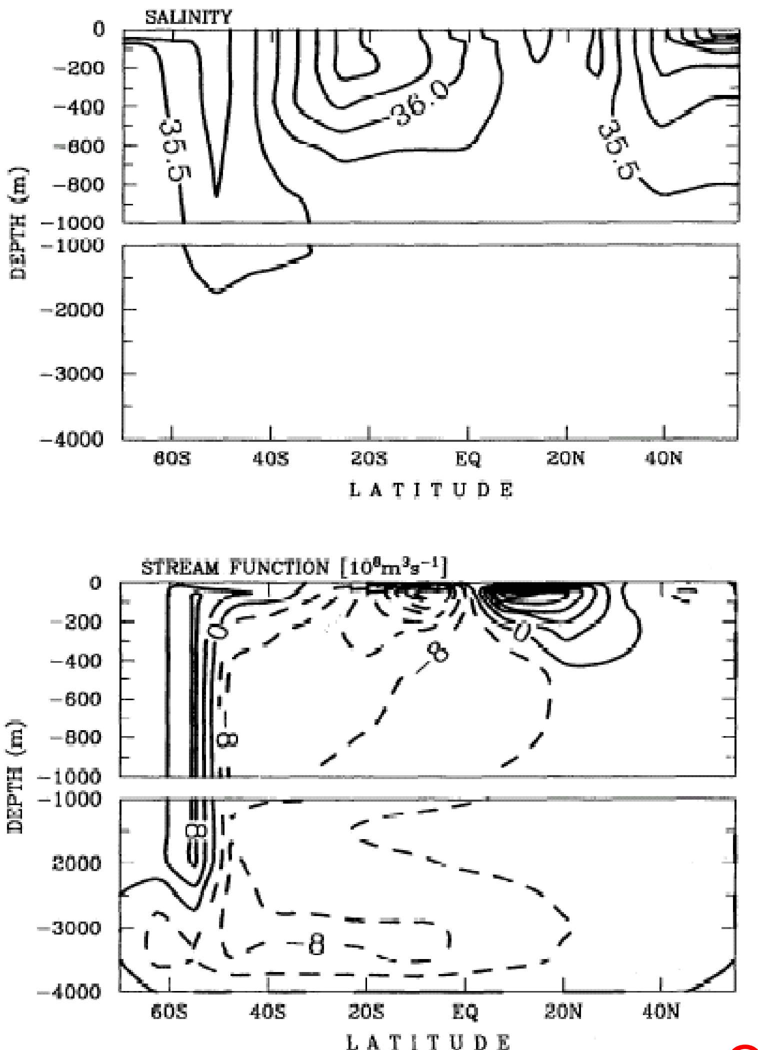

No longitudinal resolution within basins!

**Figure 2.** Geometry and resolution of the oceanic component of the climate model. Each ocean basin has area and volume that is within 5% of the observed estimates. The latitudinal resolution is shown to the left, and the vertical resolution is given in Table A1.

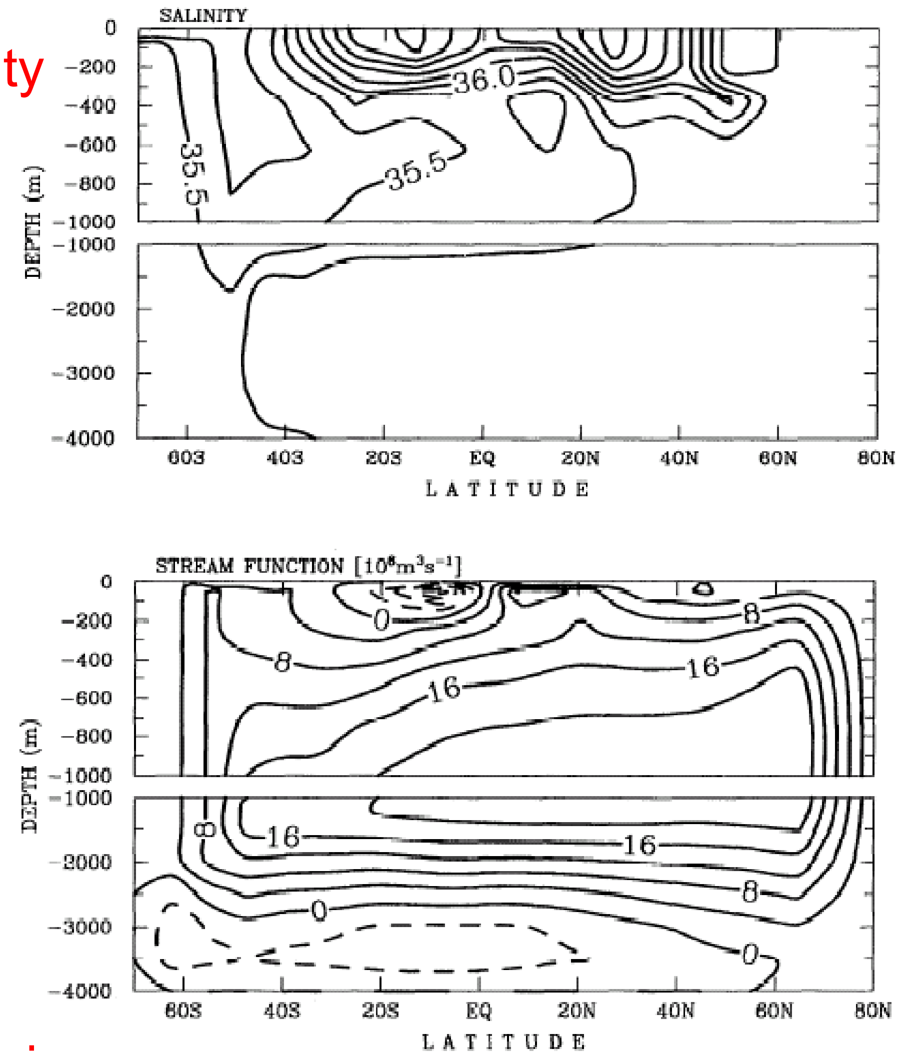
Wright and Stocker (1991, 1995)

# Wright-Stocker type zonally-averaged ocean circulation models : example output

Pacific




Atlantic




Salinity

Overturning

Stocker and Wright (1995)

# Ocean General Circulation Models (OGCMs)

- Based on primitive equations
  - solved on a grid by numerical methods
  - three-dimensional: longitude, latitude and depth are resolved

- Advantages of primitive equation models:
  - Provide most complete nowcasting and forecasting of 4-dimensional ocean state.
- Disadvantages of primitive equation models:
  - Computer resource intensive
  - Can be difficult to interpret results due to complexity

# Characteristics of atmosphere and ocean

| | Atmosphere | Ocean |
|---|---|---|
| Horizontal flow | unrestricted | restricted |
| Vertical extent | 10 km | 4 km |
| Horizontal velocity | 10 m $s^{-1}$ | 0.1 m $s^{-1}$ |
| Vertical velocity | $10^{-2}$ m $s^{-1}$ | $10^{-4}$-$10^{-5}$ m $s^{-1}$ |
| Rossby radius at 30°N/30°S | 1000 km | 40 km |
| Required resolution | 5° | 1/5° |
| Density contrast | ~$4x10^{-2}$ | ~$2x10^{-3}$ |
| Equilibrium timescale | days | 100-1000 years |
| Heat gain | mainly from below | from above |
| Heat loss | entire column | at the surface |
| Heat capacity | negligible | large |

# Parameterization

- Parameterizations are based on quantities that can more easily be observed or calculated.
  - Three-dimensional turbulence
  - Convection
  - Internal wave breaking
  - Unresolved eddies

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# Parameterization

Why are parameterizations important?

- Small-scale processes act to distribute heat away from a source.
  - If the larger scale currents were very weak, so that there were little or no advection, and the model did not account for subgridscale processes, then the model ocean would get hotter and hotter near a source of heat, whereas in the real ocean, turbulent diffusion would dissipate the heat.
- Wind blowing across the surface of the ocean imparts momentum to the ocean through friction.
- Near the bottom of the ocean, friction acts to slow down the flow.
  - In shallow coastal regions, the part of the water column affected by bottom friction may extend all the way to the surface.
- Large-scale motions serve as a source of energy for smaller-scale motions producing an energy cascade from the largest scales down to the molecular scale.
  - No complete theory exists to describe this behavior.

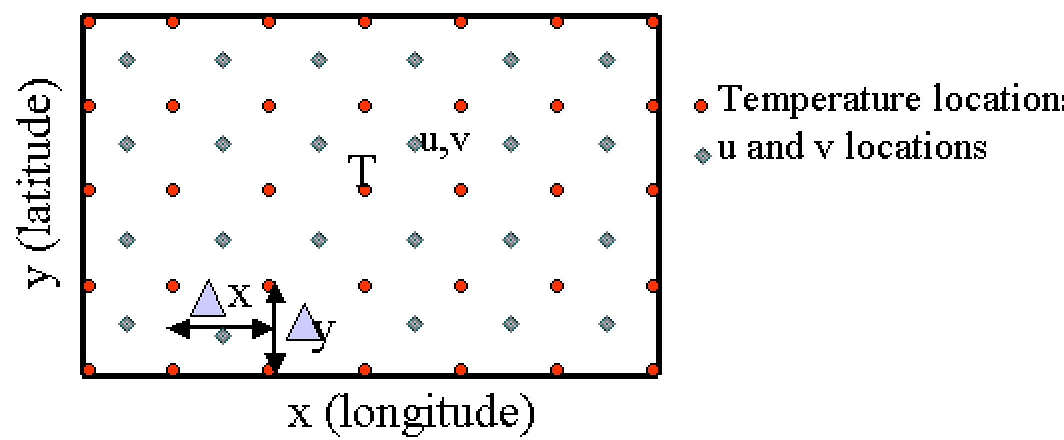
# Discretization

- Usually "finite-difference" or "finite-volume" (as in our advection or energy balance problems)
- In the horizontal: "staggered" grid
- In the vertical:
  - z-coordinate
  - s-coordinate (terrain-following)
  - isopycnal coordinate (equal-density surfaces)

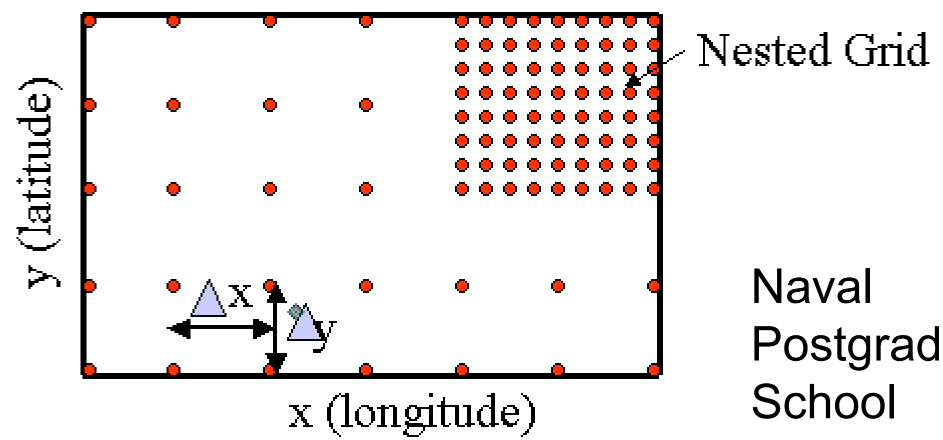
# Horizontal Grid Types

The “B” grid scheme is used in many finite-difference ocean models today.

“B” Grid




A nested grid allows for higher resolution in areas where it is needed, without expending computer resources in areas where it is not needed.

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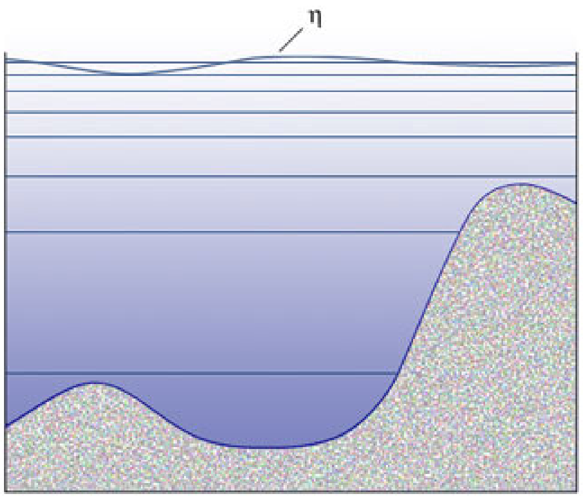
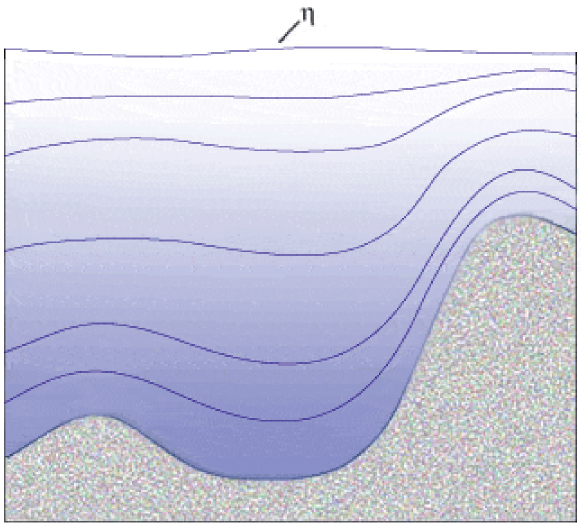
# Horizontal resolution

| Approximate resolution | Name | Characteristics |
| --- | --- | --- |
| ≥1.0° | coarse | No eddies |
| ~0.5° | "eddy-permitting" | Only meso-scale eddies |
| ≤0.2° | "eddy-resolving" | Eddies generates with right strength and at realistic rate |

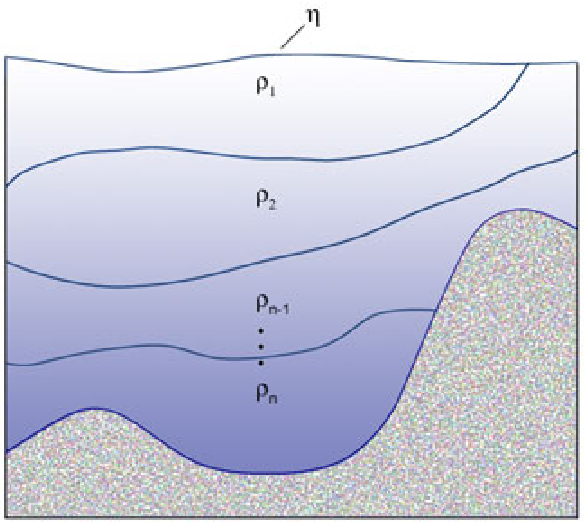
# Vertical Grid Types




**z-coordinates.** In this coordinate system, the vertical coordinate is depth, or "z".

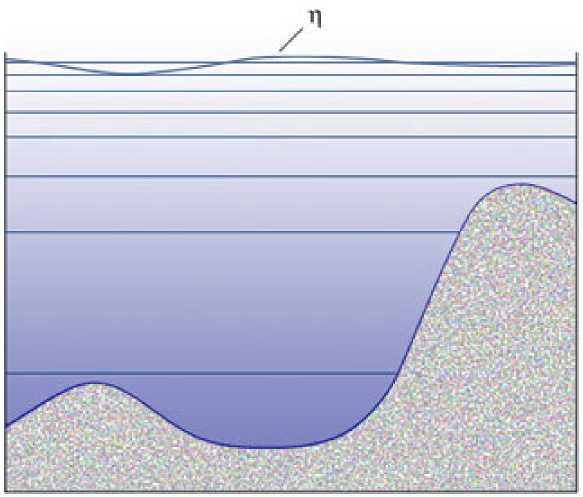



**sigma (σ)-coordinates.** In this type of model, the vertical coordinate follows the bathymetry.

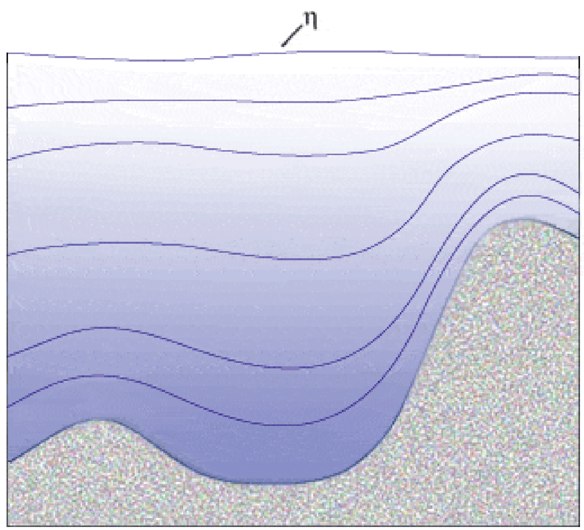



**isopycnal coordinates/ layered models.** These models use the potential density referenced to a given pressure as the vertical coordinate.

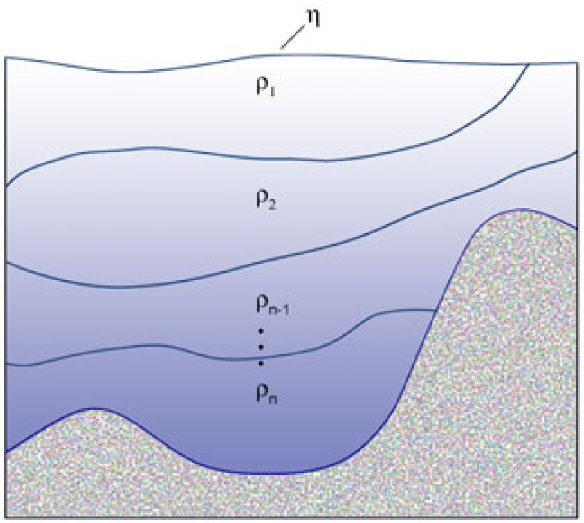
# Vertical Grid Types



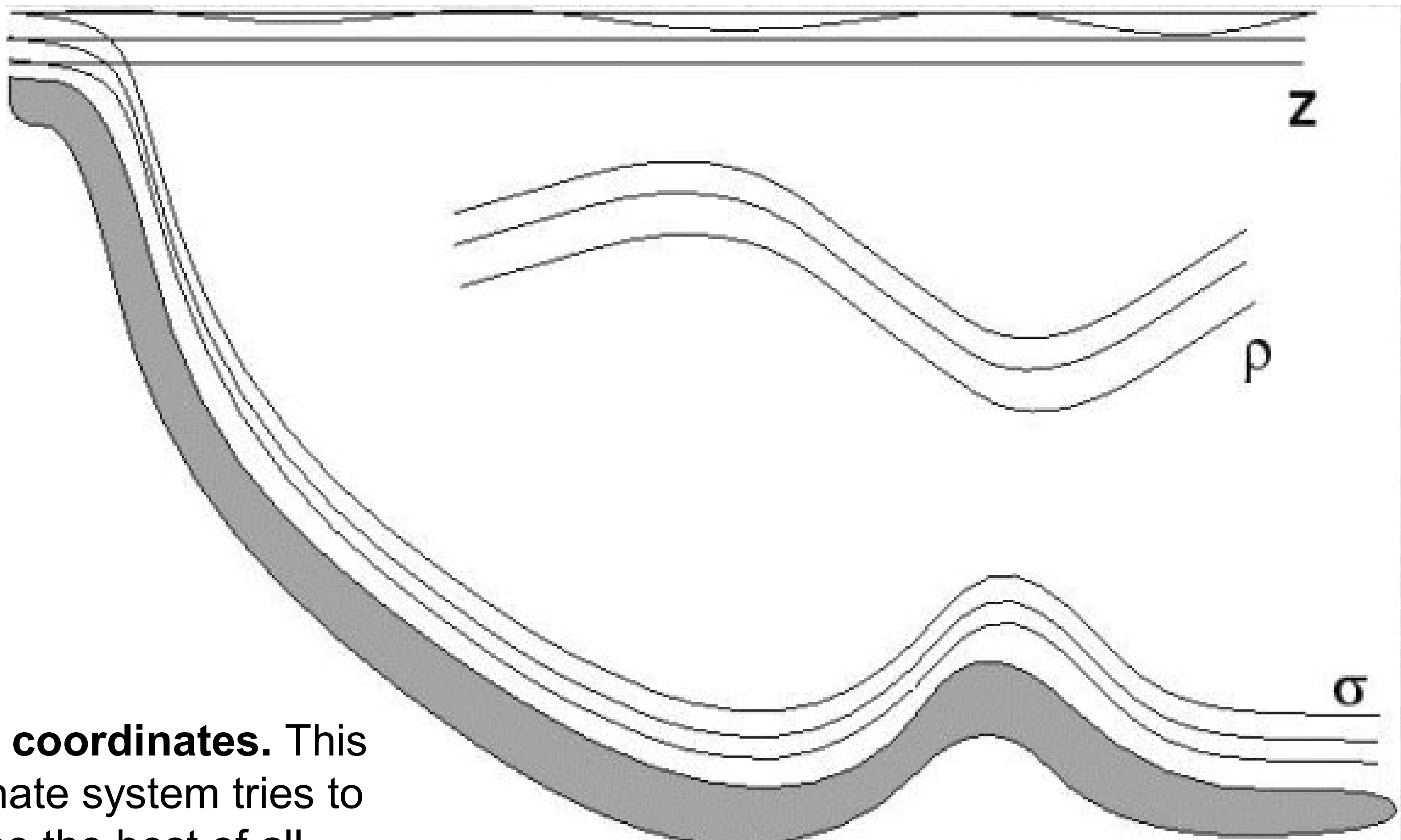

**z-coordinates** provide fine resolution needed to represent turbulence, but intersect bathymetry and may cause unrealistic vertical velocities.




**sigma (σ)-coordinates** are most appropriate for continental shelf and coastal regions, but have difficulty handling sharp topographic changes and can give rise to unrealistic flows.




**isopycnal coordinates/ layered models** preserve water mass characteristics through centuries of integration, but have limited applicability in coastal regions and surface and bottom boundary layers.



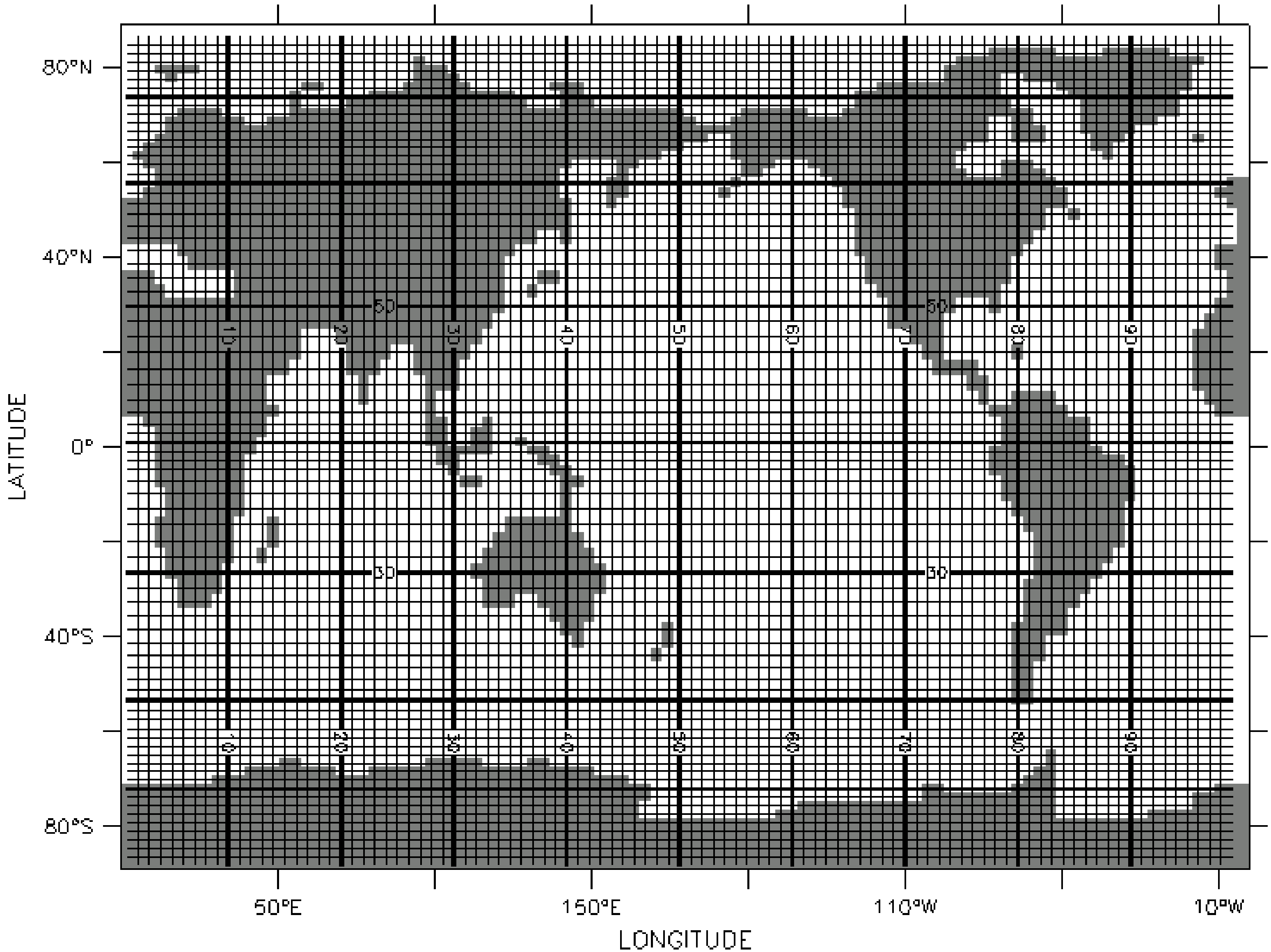

**hybrid coordinates.** This coordinate system tries to combine the best of all three coordinate systems in use.

Courtesy of Eric Chassignet (U. Miami)

# Example of a horizontal grid in an OGCM

$1.8° < \Delta\phi < 3.6°$

Finer at low and high latitudes




$\Delta\lambda = 3.6°$

# Examples for vertical grids in an OGCM (*z*-coordinate model)

**Even depth spacing** (rarely used) | **Uneven depth spacing**

Depth

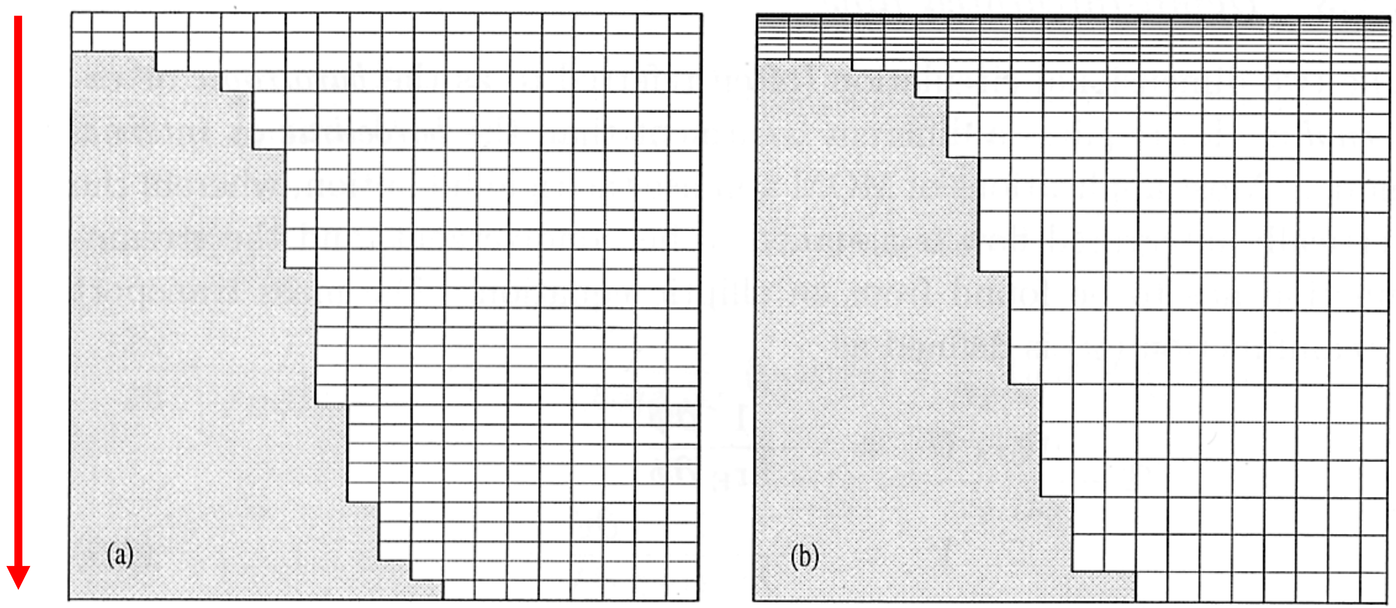


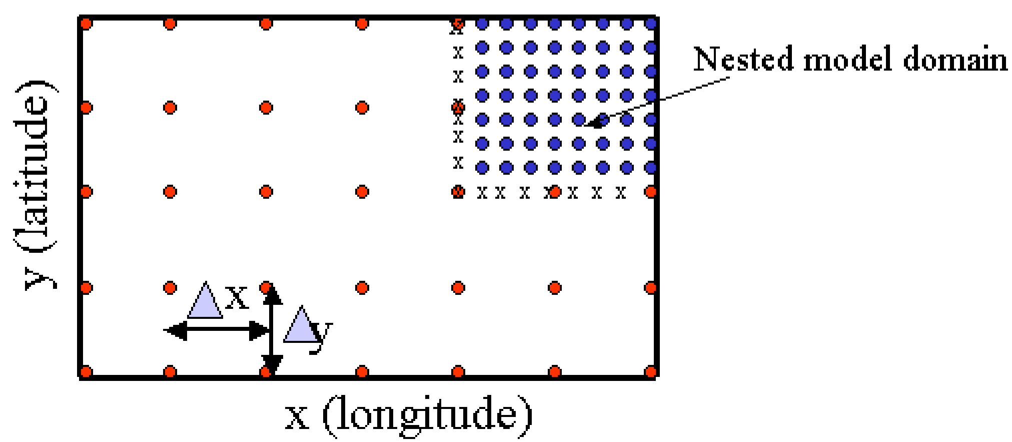

Fig. 4.1 Vertical discretization of a tanh-shaped topography for a geopotential (z) coordinate model and 30 levels: (a) equidistant grid spacing; (b) typical discretization with higher resolution near the surface.

Haidvogel and Beckmann (1999)

# Lateral Boundary Conditions

- **Closed boundary** – e.g. coastline or shelf break
- **Open Boundary** – for the sides of the domain not bounded by land
- **Periodic or Cyclic Boundary Conditions** – appropriate for channel flow or global model.

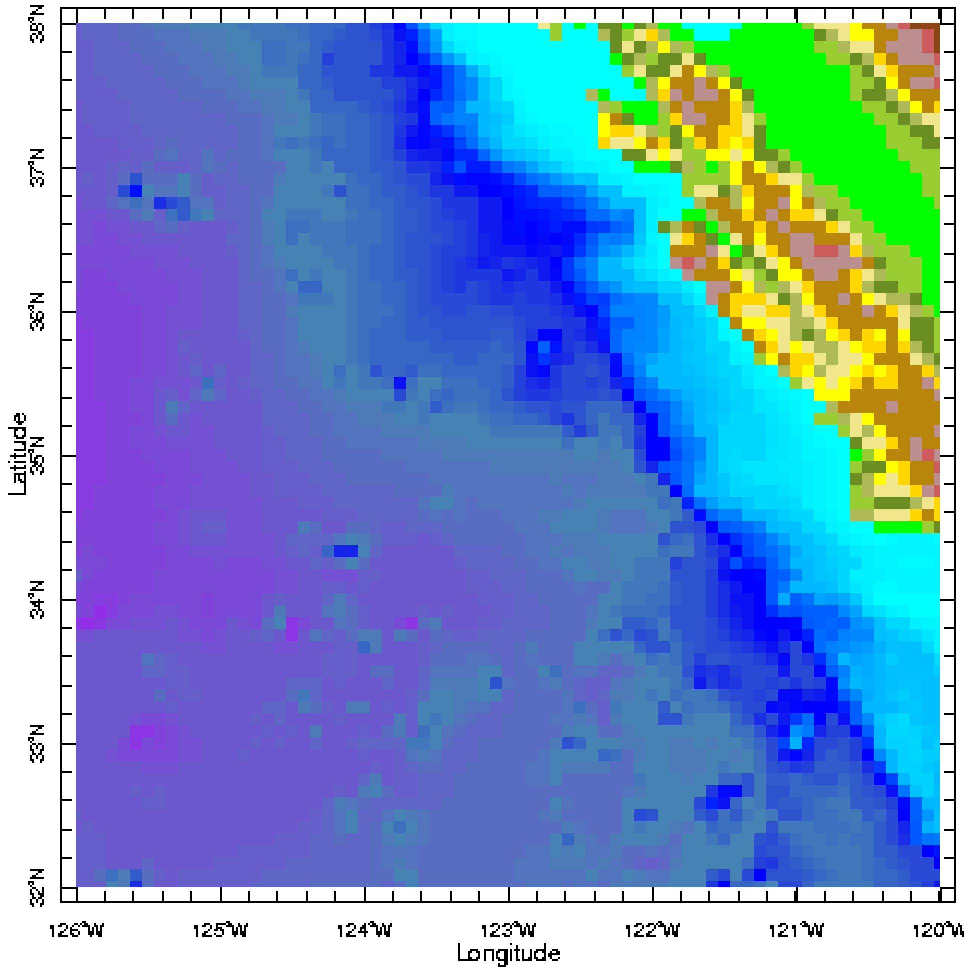
Values from the larger domain (red dots) are interpolated and used as boundary conditions (denoted by x's) in the nested model.



# Bathymetry

- Some currents in the ocean are influenced by topography (topographic steering: Coriolis parameter/depth = constant )
- Friction dampens flow
  - At the Bottom
  - Near the coast

Example of bathymetry at 1/5°
(California margin)




| | | | |
|---|---|---|---|
| Top: | N 38 | Bottom: | N 32 |
| Left: | W 126 | Right: | W 120 |

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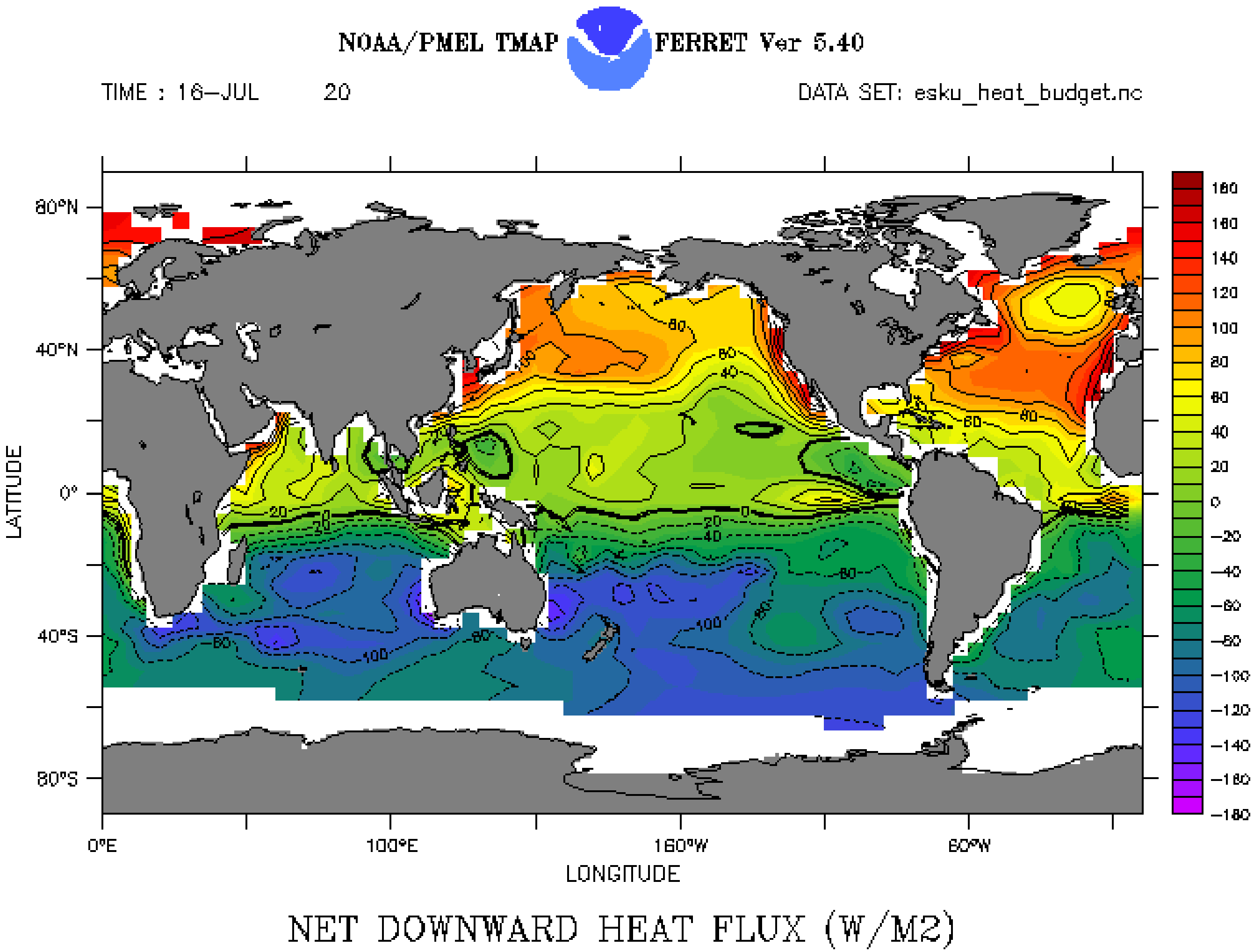
# Forcing



NOAA/PMEL TMAP
FERRET Ver 5.40
TIME : 16-JUL 20
DATA SET: esku_heat_budget.nc
80°N
40°N
0°
40°S
80°S
LATITUDE
0°E
100°E
160°W
60°W
LONGITUDE
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
NET DOWNWARD HEAT FLUX (W/M2)

# Forcing

- Wind forcing
  - moves the ocean: “Much of the ocean's variability, especially in the top layers, is wind driven. Realistic simulations require realistic winds to be used.”
- Buoyancy forcing
  - The temperature of the surface waters is influenced by
    - Shortwave radiation
    - Longwave radiation
    - Latent heat
    - Sensible heat
  - The salinity of the surface waters is influenced by
    - Evaporation (E)
    - Precipitation (P)
    - River runoff (R)
- Tidal forcing

# Summary: boundary conditions for an OGCM

- Lateral boundary conditions
  - Land-sea mask/continental configuration
- Bathymetry
- Surface boundary conditions
  - Wind stress
  - Net heat flux (or surface temperature)
  - Net freshwater flux (or surface salinity)

# Initialization

- From climatology
- From previous model run (restart)
- Spin up
  - How long does it take for the ocean model to reach equilibrium?
    - The deep ocean requires hundreds to thousands of years to adjust.
    - The upper ocean only requires about 50 years or so.

# Numerical solution

- Must be implemented as computer code (mostly in Fortran)
- Must satisfy stability criteria

# Numerical solution

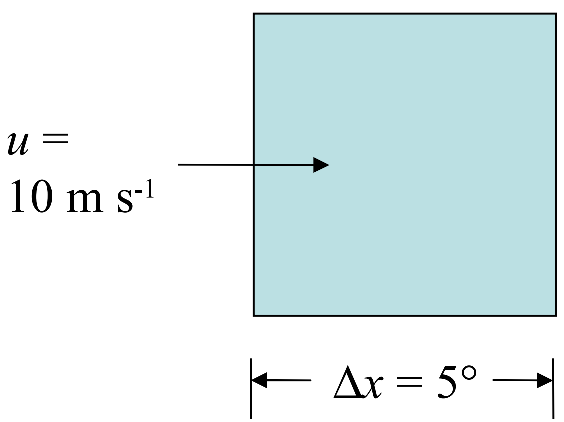
Example of stability criterion for many explicit time-stepping schemes: Courant-Friedrich-Levy (CFL) criterion

$$\Delta t \leq \frac{\Delta x}{u}$$

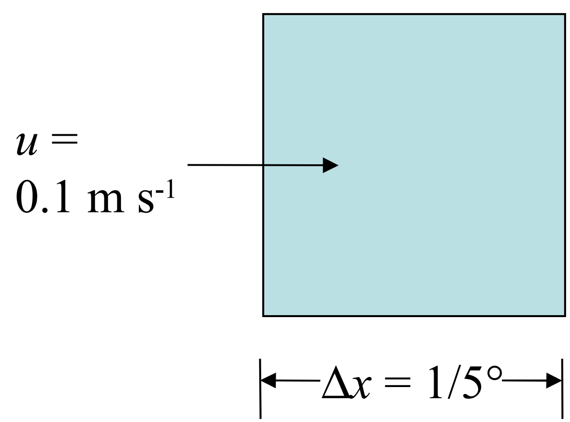
“No transport faster than one grid cell per timestep”

➔ Puts severe constraint on time step and determines duration of model simulation

**Atmospheric grid cell**

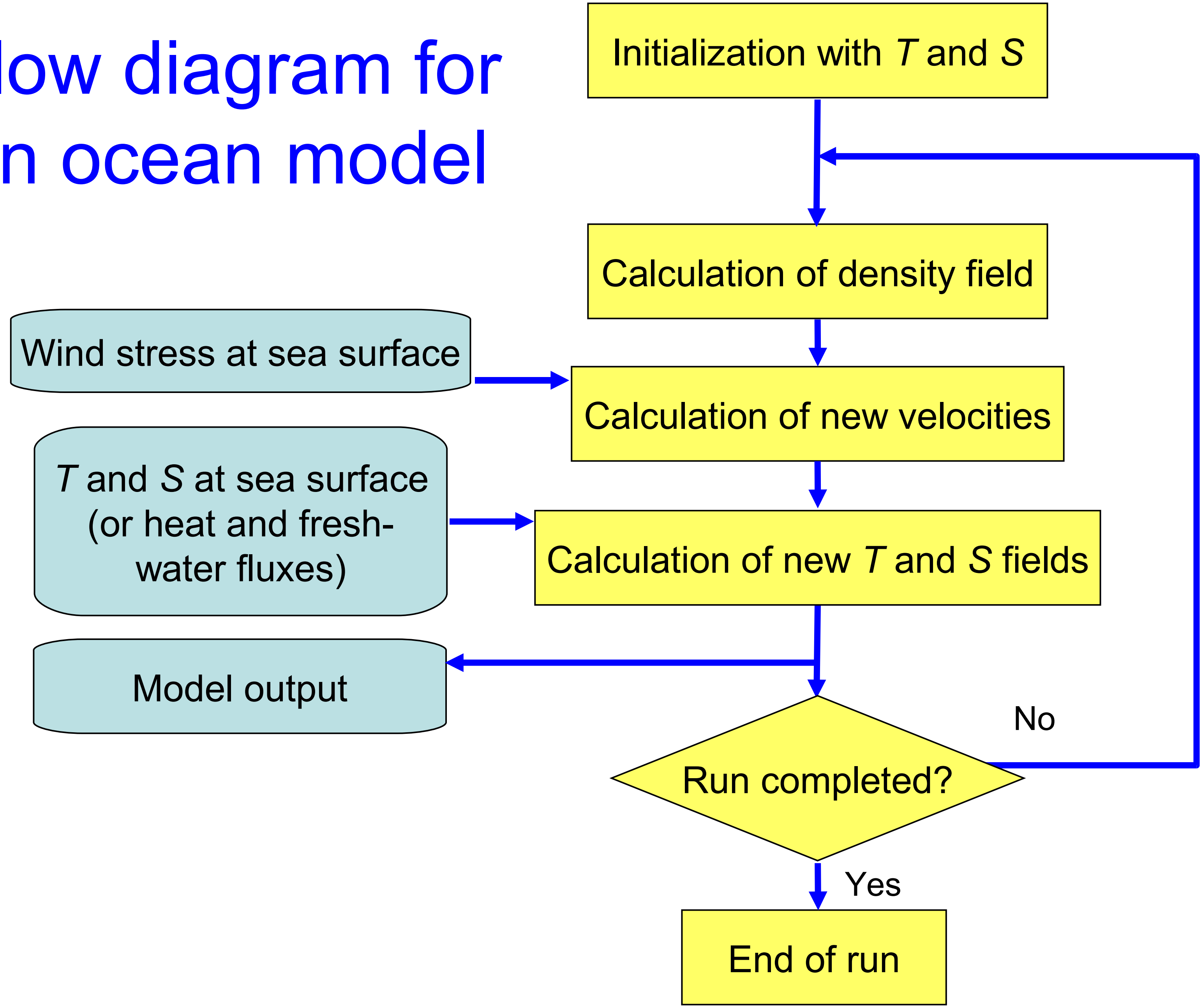



**Ocean grid cell**




Given a typical horizontal velocity and a resolution sufficient to simulate eddies, what would be the maximum time step $\Delta t$ still satisifying the CFL criterion in an atmospheric and ocean GCM, respectively?

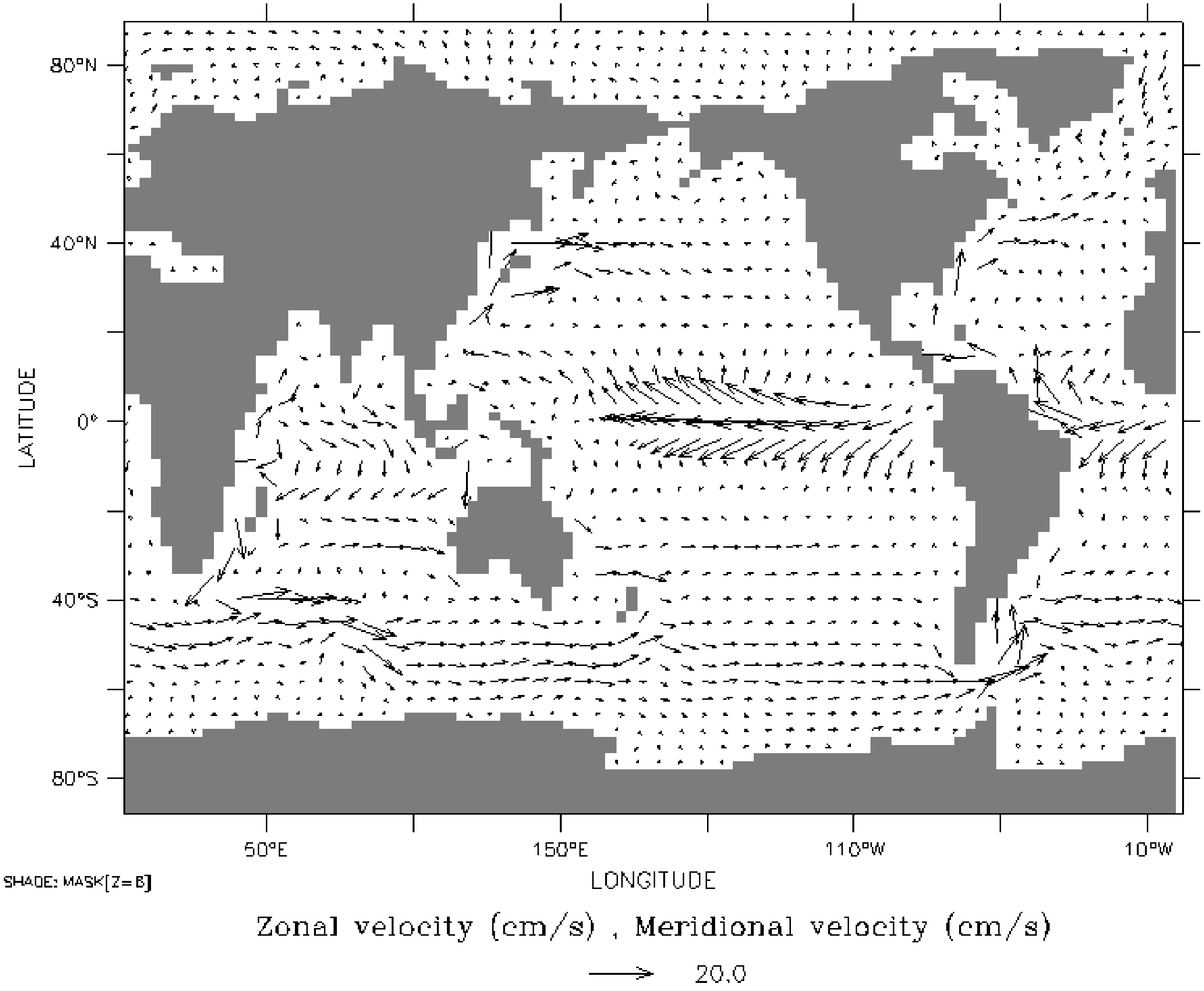
# Flow diagram for an ocean model



# OGCM Output

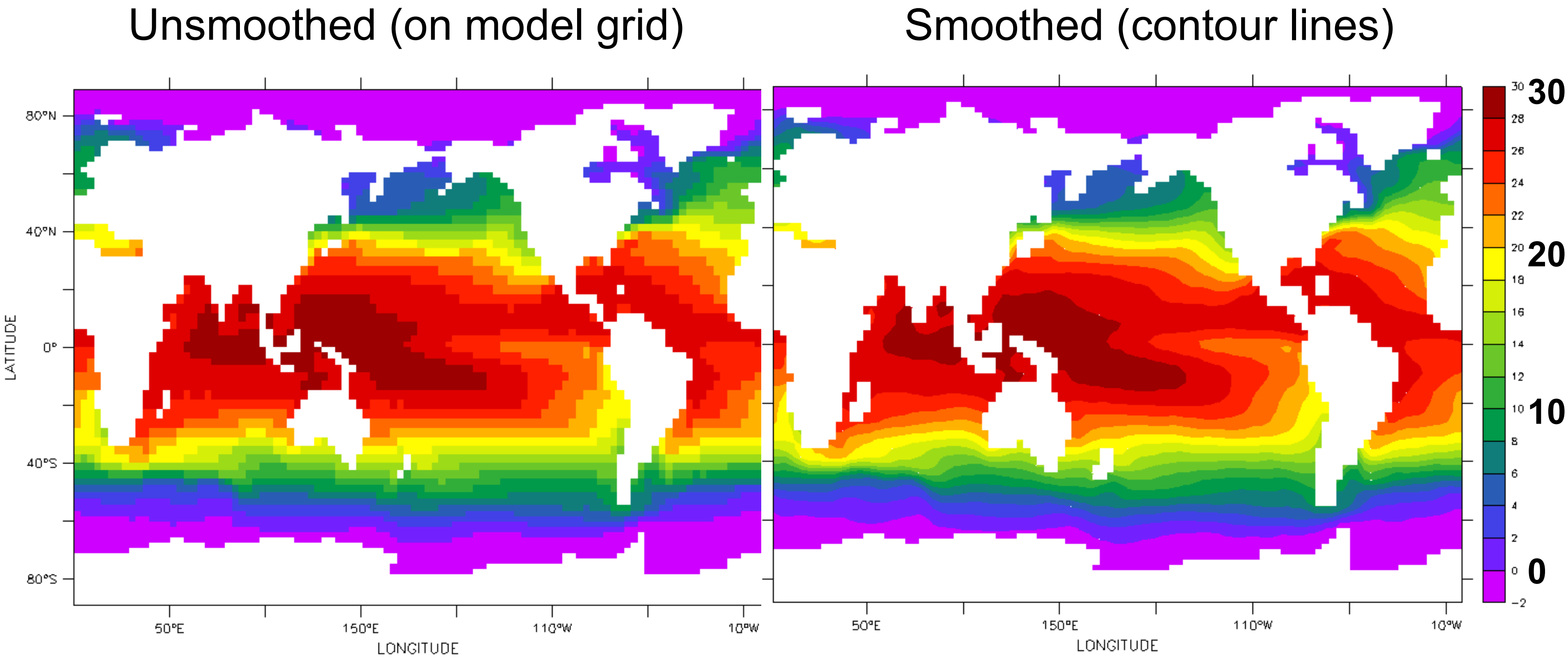
- 2-d or 3-d distributions of state ("prognostic") variables:
  - Temperature
  - Salinity
  - Velocity
- Many diagnostic variables, e.g.:
  - Vertical velocity
  - Density
  - Meridional (north-south) heat transport
  - Meridional volume transport
  - Convection depth

# Modeled velocity at 18 m Depth




Model: MOM3 ($\Delta\phi$ = 1.9 to 3.9°, $\Delta\lambda$ = 3.6°, 27 layers)     Data are annual averages

# Modeled Sea-Surface Temperature (°C, at 6 m Depth)

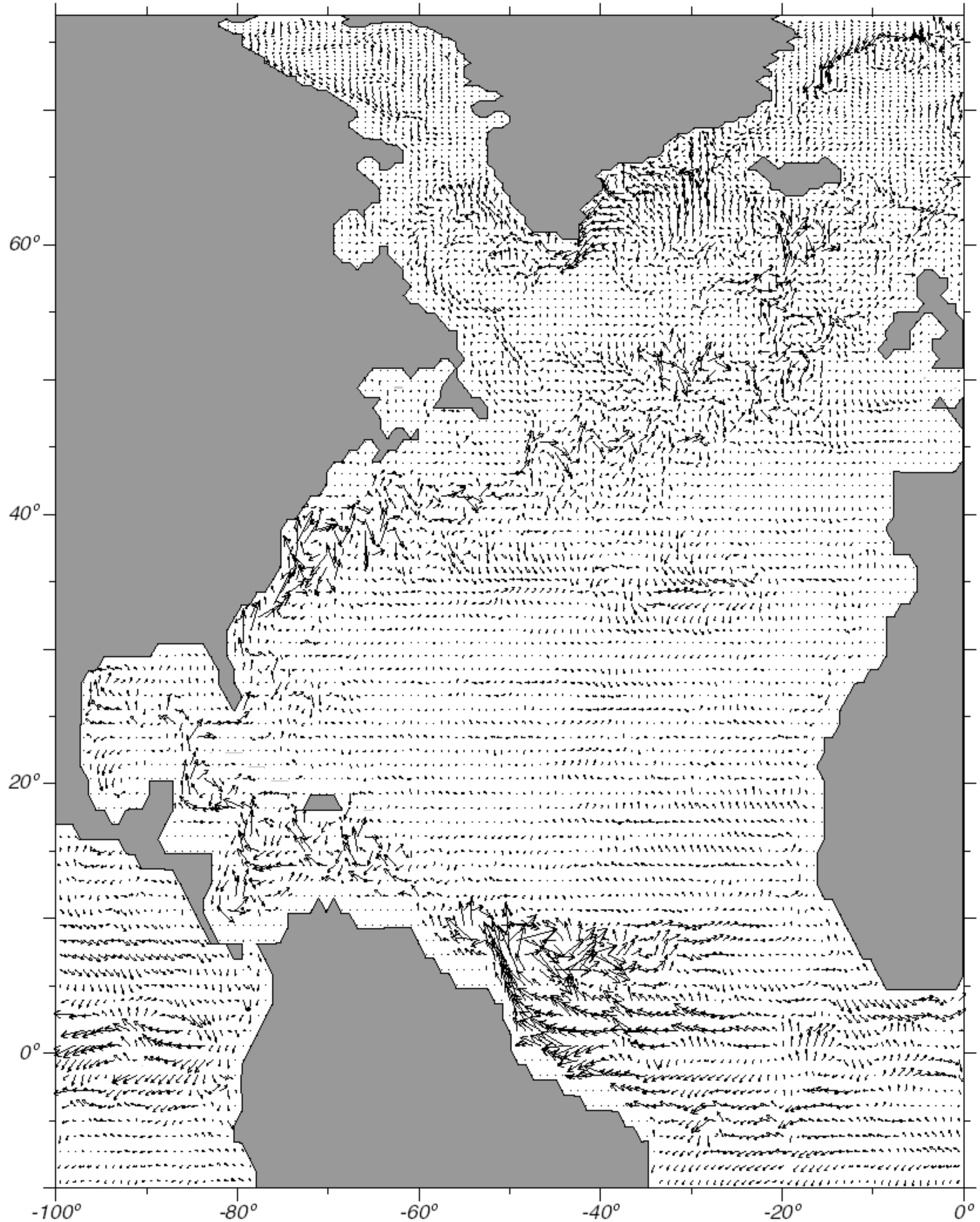



Model: MOM3 ($\Delta\phi$ = 1.9 to 3.9°, $\Delta\lambda$ = 3.6°, 27 layers)

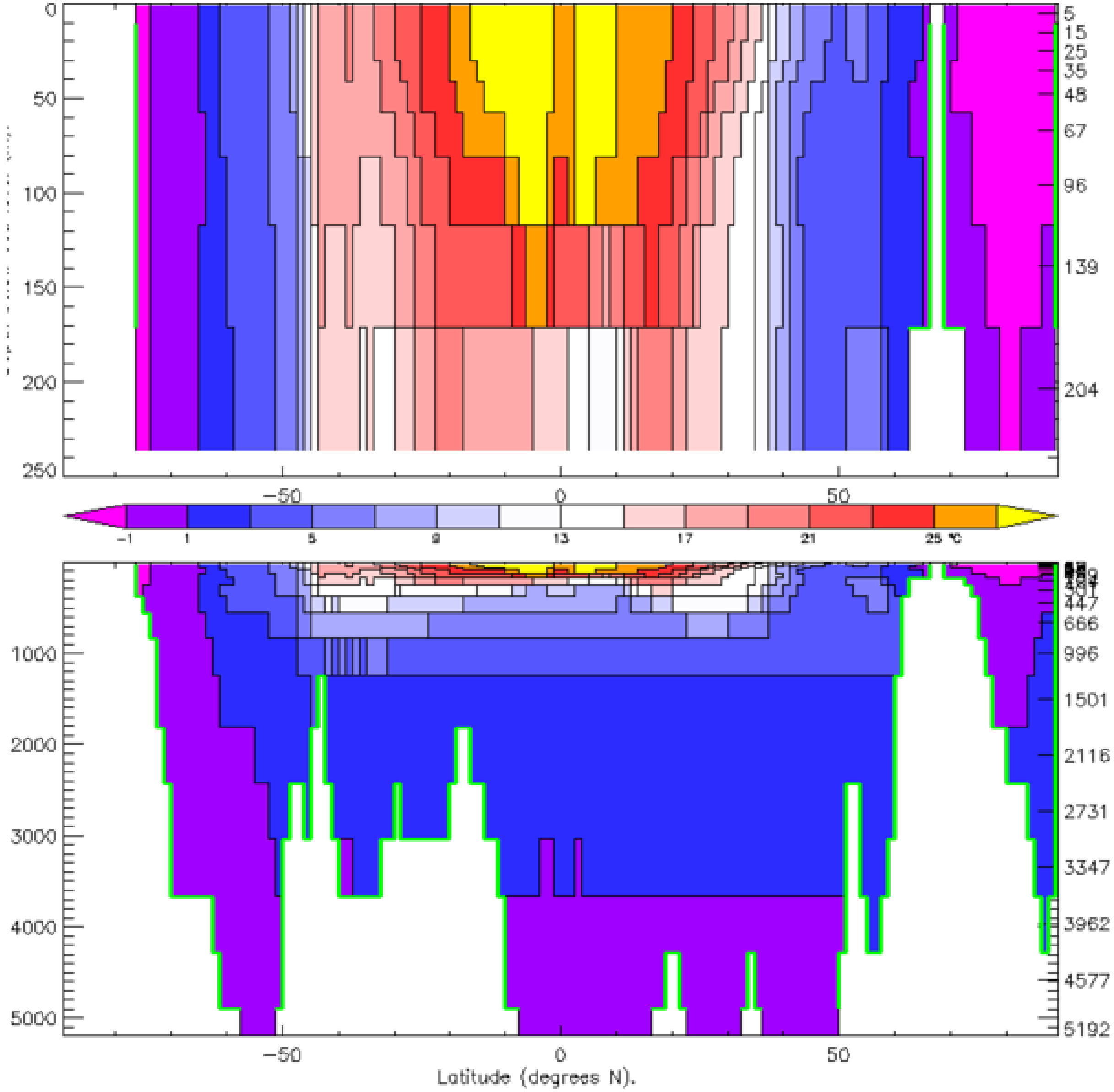
Data are annual averages

# Example of a predictive model

Near-surface geostrophic currents on October 1, 1995 calculated by the "Parallel Ocean Program" numerical model developed at the Los Alamos National Laboratory.




Stewart (2006, Figure 15.1)




Ocean temperatures (annual mean at 180° E) in the "HadOM3" ocean model. This ocean model has a resolution of 1.25°x1.25°, 20 vertical levels, and a timestep of 1 hour.

(Courtesy of William M. Connolley)

# Meridional streamfunction:
# A measure of the large-scale circulation

- Streamfunction $\Psi$ (or „overturning“) is a volume transport, i.e.

  volume transport = velocity × cross-sectional area

  Recipe: First compute zonally (east-west) averaged meridional (northward) velocity. Then integrate from the surface of the ocean to its bottom and record the value of this integral at each depth.

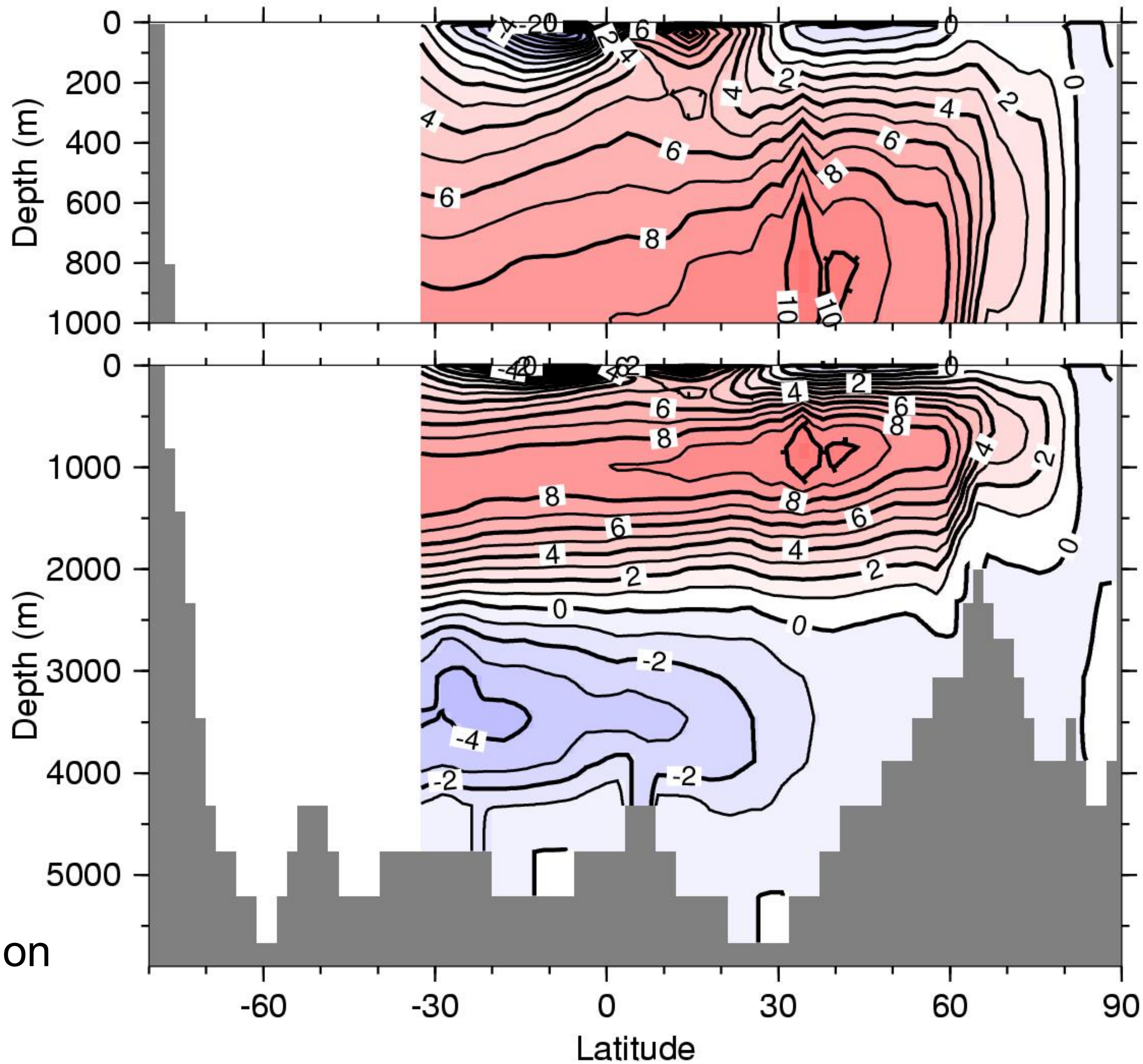
$$\Psi(z) = \int_0^z \int_{x_1}^{x_2} v \, dx \, dz$$

  With $x_{1,2}$ = eastern/western basin boundaries (Carstesian coordinates),

  $z$ = depth, and $v$ = northward velocity.

- Common unit of $\Psi$ is a Sverdrup with 1 Sv = $10^6$ m$^3$ s$^{-1}$.
- Streamlines are lines of constant $\Psi$ values.
- Rule: Volume transport between any two streamlines = difference between corresponding streamfunction values.

# Atlantic Ocean Meridional Overturning [Sv]




Positive values:
→ Clockwise rotation

Negative values:
→ Counter-clockwise rotation

"Modular Ocean Model (MOM) version 2"

Paul and Schäfer-Neth (2003)

# Current challenges in ocean modeling

- According to Wunsch (2006, 2007), existing climate models
  - lack resolution (either vertical or horizontal) to properly compute the behavior of fresh water and its interaction with underlying ocean and overlying atmosphere
  - use physically inappropriate ("salt-flux") boundary condition
  - have almost always been run with fixed diffusion coefficents
  - ignore wind as prime mover (e.g. through tides)

Wunsch, C. (2006). Abrupt climate change: An alternative view. Quaternary Research, 65, 191-203.